The Spectroscopic Orbit of the Planetary Companion Transiting HD 209458[1]

Tsevi Mazeh,[2] Dominique Naef,[3] Guillermo Torres,[4] David W. Latham,[4] Michel Mayor,[3] Jean-Luc Beuzit,[5] Timothy M. Brown,[6] Lars Buchhave,[7] Michel Burnet,[3] Bruce W. Carney,[8] David Charbonneau,[4,6] Gordon A. Drukier,[2] John B. Laird,[9] Francesco Pepe,[3] Christian Perrier,[5] Didier Queloz,[3] Nuno C. Santos,[3] Jean-Pierre Sivan,[10] Stéphane Udry,[3] Shay Zucker[2]

ABSTRACT

We report a spectroscopic orbit with period $P = 3.52433 \pm 0.00027$ days for the planetary companion that transits the solar-type star HD 209458. For the metallicity, mass, and radius of the star we derive [Fe/H]$= 0.00 \pm 0.02$, $M_* = 1.1 \pm 0.1\, M_\odot$, and $R_* = 1.3 \pm 0.1\, R_\odot$. This is based on a new analysis of the iron lines in our HIRES template spectrum, and also on the absolute magnitude and color of the star, and uses isochrones from four different sets of stellar

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[2]School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel

[3]Observatoire de Genève, 51 ch. des Maillettes, CH 1290 Sauverny, Switzerland

[4]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

[5]Laboratoire d'Astrophysique, Observatoire de Grenoble, BP 53, F-38041 Grenoble, France

[6]High Altitude Observatory, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000. NCAR is sponsored by the National Science Foundation.

[7]Astronomical Observatory Niels Bohr Institute for Astronomy, Physics & Geophysics Copenhagen University, Denmark

[8]Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-3255

[9]Department of Physics & Astronomy, Bowling Green State University, Bowling Green, Ohio 43403

[10]Observatoire de Haute-Provence, F-04870, St-Michel l'Observatoire, France

evolution models. Using these values for the stellar parameters we reanalyze the transit data and derive an orbital inclination of $i = 85\overset{\circ}{.}2 \pm 1\overset{\circ}{.}4$. For the planet we derive a mass of $M_p = 0.69 \pm 0.05\,M_{\rm Jup}$, a radius of $R_p = 1.54 \pm 0.18\,R_{\rm Jup}$, and a density of $\rho = 0.23 \pm 0.08\,{\rm g\,cm^{-3}}$.

Subject headings: binaries: eclipsing — planetary systems — stars: individual (HD 209458) — techniques: radial velocities

1. INTRODUCTION

We report in this Letter on our spectroscopic observations of HD 209458, observations that led to the discovery of a transiting planet with an orbital period of 3.5 days.

We have been observing HD 209458 since August 1997 as one of the targets in two large independent radial-velocity surveys, both searching for extrasolar planets around solar-type stars. One program uses HIRES (Vogt et al. 1994) on the Keck I telescope, and the other uses ELODIE (Baranne et al. 1996) on the 1.93-m telescope at Observatoire de Haute Provence (France). In June 1999, after observations from both efforts showed that the radial velocity of HD 209458 was variable, additional frequent observations were obtained with ELODIE, as well as with CORALIE (Queloz et al. 1999) on the new 1.2-m Swiss telescope at La Silla.

In August 1999 the identity of HD 209458 and its orbital elements were provided to D. Charbonneau and T. Brown so that they could look for transits with the STARE photometric instrument (Brown & Kolinski 1999). Two transits were successfully observed in September 1999 (Charbonneau et al. 2000; hereafter C00). An independent discovery in November 1999 of the planetary orbit, as well as the detection of a transit ingress, are reported by Henry et al. (2000).

Transit observations together with an orbital solution allow us to determine directly the mass, radius, and density of the planet, provided we have good estimates for the mass, radius, and limb darkening of the star (e.g., C00). We describe in this Letter our efforts to derive better estimates for these parameters.

2. OBSERVATIONS

One of the two radial-velocity projects, the results of which we report here, is the G Dwarf Planet Search (Latham 2000). The sample for this project is composed of more than 1000 targets whose effective temperatures, luminosities, chemical compositions, and Galactic-population memberships have been determined using precise Strömgren photometry (Olsen 1993; private communications). In addition, the radial velocities of these stars were known to be constant at a precision of 300–600 $\mathrm{m\,s^{-1}}$, based on more than ten years of observations with the CORAVELs (Mayor 1985) and the CfA Digital Speedometers (Latham 1985, 1992).

The observations for this project were performed with HIRES and its iodine gas-absorption cell (Marcy & Butler 1992) on the Keck I telescope. The G Dwarf Planet Search observing strategy is designed to carry out an initial reconnaissance of the sample stars, with the immediate goal of identifying the stars whose radial velocity is modulated with an amplitude of about 50 $\mathrm{m\,s^{-1}}$ or larger. To increase the number of target visits we concede velocity precision, and therefore have exposed no longer than needed to achieve a precision of 10 $\mathrm{m\,s^{-1}}$. Radial velocities are derived from the spectra with TODCOR (Zucker and Mazeh 1994) — a two dimensional correlation algorithm. Although we are still in the development stage of our software (Zucker, Drukier & Mazeh, in preparation), preliminary results from the global analysis of the 675 stars with two or more iodine observations show that we are already close to achieving our goal of 10 $\mathrm{m\,s^{-1}}$ or better.

The other program whose results are presented here is the ELODIE planet search survey (Mayor & Queloz 1995a). After the discovery of the planetary companion around 51 Peg (Mayor & Queloz 1995b), the surveyed sample was extended to about 320 northern hemisphere solar-type stars brighter than $m_V = 7.65$ and with small projected rotational velocities ($v \sin i$ from CORAVEL, Benz & Mayor 1984). From CORAVEL data, the stars in this sample were known to have constant radial velocities at a 300 $\mathrm{m\,s^{-1}}$ precision level. Radial-velocity measurements are obtained with the ELODIE echelle fiber-fed spectrograph (Baranne et al. 1996) mounted on the Cassegrain focus of the 1.93-m telescope of the Observatoire de Haute-Provence. The reduction technique used for this sample is known as the “simultaneous Thorium-Argon technique” described by Baranne et al (1996). The precision achieved with this instrument is of the order of 10 $\mathrm{m\,s^{-1}}$ over more than 3 years.

After the two independent detections of the short-term variability of HD 209458 by the HIRES and ELODIE teams, we decided to add this object to the CORALIE planet search sample (Udry et al. 1999a,b) in order to gather more radial-velocity data and therefore increase the precision of the orbital elements. The precision achieved with CORALIE is of the order of 7–8 $\mathrm{m\,s^{-1}}$ over 18 months. To check for other possible sources of line shifts besides orbital motion we computed the mean bisector profiles (as described by Queloz et al. 2000, in preparation) for all the ELODIE and CORALIE spectra. No correlation between the observed velocities and the line profiles was detected, convincing us that the planetary interpretation was correct even before transits were detected.

3. RADIAL-VELOCITY ANALYSIS

As of November 16, 1999, we had a total of 150 radial-velocity measurements of HD 209458 available for analysis: 11 from HIRES, 31 from ELODIE, and 108 from CORALIE. Initially we applied shifts of -5 m s^{-1} to the ELODIE velocities and -14780 m s^{-1} to the HIRES measurements to bring them to the CORALIE system, the latter offset being much larger due to the arbitrary zero point of the HIRES velocities (Zucker, Drukier & Mazeh, in preparation). To account for possible errors in these shifts, the orbital solutions described below included two additional free parameters — Δ_{H-C} and Δ_{E-C} for the HIRES and ELODIE shifts — along with the orbital elements.

In addition, the two transit timings recorded by C00 provide useful information on the orbital period and T_c, the time of inferior conjunction. These timings were therefore included in the derivation of the spectroscopic orbital elements, and we treated them as independent measurements with their corresponding uncertainties.

In a preliminary solution weights were assigned to each observation based on the internal errors. From this fit we computed the RMS residuals separately for each data set – σ_H, σ_E, and σ_C — and then scaled the internal errors for each instrument to match the corresponding RMS residuals on average. We re-solved for the orbital parameters, and the procedure converged in one iteration with essentially no change in the elements.

Tests allowing for a non-circular Keplerian orbit for HD 209458 resulted in an eccentricity indistinguishable from zero: $e = 0.016 \pm 0.018$. We therefore assume in the following that the orbit is circular. Our final orbital solution is represented graphically in Figure 1. The elements are given in Table 1, where the value of the planetary mass, M_p, depends on the inclination angle and on the adopted stellar mass, M_*, to the power of 2/3. The orbital elements reported by Henry et al. (2000) are consistent with our results, although their quoted errors are substantially larger. Robichon & Arenou (2000) have identified three transits in the Hipparcos photometry and have derived a more precise period, $P = 3.524739 \pm 0.000014$ d, consistent with the value of Table 1 within 1.5-σ.

4. STELLAR PARAMETERS

In this section we compare the results of two different approaches for estimating the mass and radius of HD 209458. In the first approach we rely on the effective temperature,

$T_{\rm eff}$, and the surface gravity, $\log g$, derived from a fine analysis of the iron lines in the HIRES template spectrum of HD 209458. In the second approach we take advantage of the accurate distance available from the Hipparcos astrometric mission (ESA 1997) and rely on the stellar absolute magnitude and observed color. For both approaches we matched theoretical isochrones from four different sets of stellar evolution models with the location of HD 209458 in the corresponding parameter plane, estimating the stellar mass, radius and age.

The stellar models depend sensitively on the metallicity, and therefore a critical first step for both approaches is to determine the metallicity. An analysis of eight spectra obtained with the CfA Digital Speedometers (Latham 1992) with the techniques reported by Carney et al. (1987) gave $T_{\rm eff} = 5975$ K, $\log g = 4.25$, and $[{\rm m/H}] = +0.11 \pm 0.1$. Another independent analysis of the cross-correlation dips from CORAVEL observations (Mayor 1980 as revised by Pont 1997 using primary calibrators by Edvardsson et al. 1993) gave $[{\rm Fe/H}] = -0.14 \pm 0.1$.

This large range in metallicity values, -0.14 to $+0.11$, implied a large uncertainty in the mass and radius of HD 209458, so we undertook a detailed analysis of selected Fe I and Fe II lines measured on our HIRES template spectrum, which has a resolving power of about 70,000 and signal-to-noise ratio per resolution element of about 300. We adopted a line list developed by L. de Almeida (private communication) and solar gf values based on the National Solar Observatory solar flux atlas (Kurucz et al. 1984).

For this analysis of HD 209458 we used model atmospheres and computer codes based on the work of R. Kurucz. Selected weak Fe I lines were used to set $T_{\rm eff}$ by adjusting the $T_{\rm eff}$ until the plot of abundance versus excitation potential was flat. Stronger Fe I lines were then included and the microturbulent velocity was adjusted to get a flat dependence of abundance on line strength. Finally, the surface gravity was adjusted until the abundances from the Fe II and Fe I lines agreed. This analysis gave $T_{\rm eff} = 6000$ K, microturbulent velocity $\xi = 1.15\,{\rm km\,s^{-1}}$, $\log g = 4.25$, and $[{\rm Fe/H}] = 0.00$. The errors in these values are undoubtedly dominated by systematic effects, and we estimate that they are ± 50 K in $T_{\rm eff}$, ± 0.2 in $\log g$, and ± 0.02 in [Fe/H].

This approach yielded $T_{\rm eff}$ and $\log g$, as well as the metallicity. In the other approach we used the absolute magnitude and color of $M_V = 4.28 \pm 0.11$ and $B - V = +0.594 \pm 0.015$ (assuming no extinction or reddening), together with the metallicity derived from the iron lines.

In Table 2 we compare the values of the stellar mass and radius, M_* and R_*, and age that we derive for HD 209458 using the two approaches and isochrones from four different stellar evolution codes: Geneva (Schaller et al. 1992), Bertelli (Bertelli et al. 1994), Claret (Claret 1995), and Yale (Demarque et al. 1996). The results of this comparison are given in the first four lines of Table 2.

The last two lines of Table 2 demonstrate the effects of changing the stellar helium abundance and metallicity. The next-to-the-last line indicates that helium-rich models give slightly lower values of the mass and radius. The effect of changing the metallicity, with the helium scaled by the enrichment law, is illustrated by the last line. We therefore conclude that if Z = 0.019 is adopted for the solar metallicity (Anders & Grevesse 1989), all the results for the Z = 0.02 models should be reduced by about 0.01 in both mass and radius.

Note that all four sets of evolutionary models and the two approaches yielded similar results, with only small differences. The mass estimates are systematically smaller for the results based on the observational M_V vs $B-V$ plane, by about $0.05\,M_\odot$. The radius estimates are also smaller, by about $0.03\,R_\odot$. Note, however, that the good agreement between the different models may be misleading, and that systematic errors are likely to be larger. Based on all these considerations, we adopt for our best estimate of the mass and radius of HD 209458 $1.1 \pm 0.1\,M_\odot$ and $1.3 \pm 0.1\,R_\odot$. The uncertainty estimates are somewhat arbitrary, and are based mainly on the assumed uncertainty in $T_{\rm eff}$, $\log g$, M_V and $B-V$.

Using ELODIE and CORAVEL cross-correlation dip widths, we infer the projected rotational velocity (calibration by Queloz et al. (1998) for ELODIE and by Benz & Mayor (1984) for CORAVEL). The results are $v \sin i = 4.4 \pm 1$ km s^{-1} for CORAVEL and $v \sin i = 4.1 \pm 0.6$ km s^{-1} for ELODIE.

5. PLANETARY PARAMETERS

C00 present preliminary estimates of the planetary radius, R_p, and orbital inclination, i, based on initial estimates of M_*, R_*, and the R-band limb-darkening parameter c_R. We now present values for these quantities based on the more accurate analysis of the stellar parameters presented in this Letter. In addition, we present estimates of the uncertainties that combine the effects both due to the uncertainties in the stellar parameters, and due to the level of precision in the photometric measurements of the transit. All uncertainties presented below correspond to 1-σ confidence levels.

Using the calculated limb darkening coefficients presented in Claret, Díaz-Cordovés, & Giménez (1995), we adopted a value of $c_R = 0.56 \pm 0.05$, based on the values for $T_{\rm eff}$ and $\log g$ derived in the previous section. As described in C00, we then calculated the $\Delta\chi^2$ of the photometric points for the model light curve as a function of R_p and i, using the revised values of $\{M_*, R_*, c_R\}$ presented here. To evaluate the uncertainty in the derived values of R_p and i, we calculated the $\Delta\chi^2$ for all combinations of the stellar parameters at 1-σ above and below their respective best fit values. We then assign 1-σ error bars based on the intervals which are excluded with this confidence for all these combinations.

We find $R_p = 1.54 \pm 0.18\, R_{\rm Jup}$ and $i = 85\overset{\circ}{.}2 \pm 1\overset{\circ}{.}4$. The primary mass and the inclination imply (see Table 1) the planetary mass to be

$$M_p = 0.69 \pm 0.05\, M_{Jup}\ . \tag{1}$$

¿From the planetary radius and mass we calculate the density, surface gravity, and escape velocity to be $\rho = 0.23 \pm 0.08\,{\rm g\,cm^{-3}}$, $g = 720 \pm 180\,{\rm cm\,s^{-2}}$, and $v_e = 40 \pm 4\,{\rm km\,s^{-1}}$.

In the interpretation of the transit curve of HD 209458, the dominant uncertainty in the planetary parameters is due to the uncertainty in the stellar radius, rather than the observational uncertainty in the photometric points.

The planetary radius found here is larger and the orbital inclination is smaller than the values presented in C00. This is due primarily to the fact that the value of the stellar radius found here ($1.3\,R_\odot$) is larger than the one assumed in the initial analysis ($1.1\,R_\odot$). A larger star requires a larger planet crossing at a lower inclination to fit the same photometric data. The results presented here and in C00 are based on the analysis of the detailed observed transit lightcurve. Henry et al. (2000), who did not observe the full transit, assumed an inclination of 90° for the orbital inclination, and a stellar radius and mass of $1.15\,R_\odot$ and $1.03\,M_\odot$. With these assumptions they derived a planetary mass and radius of $R_p = 1.42 \pm 0.08\,R_{Jup}$ and $M_p = 0.62\,M_{Jup}$.

6. DISCUSSION

The spectroscopic orbit, when combined with the inclination derived from transits, enables us to derive the planetary mass directly. This demonstrates the power of combining spectroscopy and photometry for transiting planets (C00; Henry et al. 2000). To derive masses for non-transiting planets that have spectroscopic orbits, we are forced to turn to other approaches for determining the orbital inclination, such as astrometry (e.g., Mazeh et al. 1999; Zucker & Mazeh 2000).

HD 209458 is the first extrasolar planet whose orbital inclination is known with high precision. In principle we might be able to derive the inclination of the stellar rotational axis, if we could obtain the stellar rotational period from photometric observations. Together with the projected rotational velocity and the stellar radius derived here, this will enable us for the first time to check the assumption that the stellar rotation is aligned with the orbital motion for such short-period systems. With $v \sin i = 4.2 \pm 0.5$ km s^{-1}, alignment implies a rotational period of $P = 15.7 \pm 2.4$ days.

One unique feature of the transit technique is its ability to derive the planetary radius. As described in the review by Guillot (1999) and the references listed therein, the radius of an extrasolar giant planet is determined by its mass, age, degree of insolation, and composition. Now that an accurate measurement of the planetary radius has been made, it should be possible to infer specifics of the planetary composition, since the mass and insolation are known, and the age can be reasonably constrained based on the value of the age of the star determined above. More specifically, as described in Guillot (1999), it may be possible to calculate the amount of heavy elements for a given hydrogen/helium ratio, and to infer the presence or absence of certain atmospheric grains.

These very fascinating possibilities, together with the analysis of other known short-period extrasolar planets, like 51 Peg, τ Boo, and υ And (e.g., Ford, Rasio & Sills 1999), promise us new insights to the formation and evolution of these systems.

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FIGURE CAPTION

Fig. 1.— Radial velocities of HD209458, plotted as a function of orbital phase for the solution detailed in Table 1. The measurements of the three observational programs are represented by different symbols.

Table 1: Orbital Solution for HD 209458.

Period	3.52433 ± 0.00027	days
γ	-14.7652 ± 0.0016	$\mathrm{km\,s^{-1}}$
K	85.9 ± 2.0	$\mathrm{m\,s^{-1}}$
e	0	FIXED
T_c	$2,451,430.8238 \pm 0.0029$	HJD
$M_p \sin i$	$0.685 \pm 0.018\ (M_*/1.1M_\odot)^{2/3}$	M_{Jup}
Δ_{H-C}	$+0.2 \pm 4.7$	$\mathrm{m\,s^{-1}}$
Δ_{E-C}	$+0.5 \pm 5.1$	$\mathrm{m\,s^{-1}}$
σ_H	13.8	$\mathrm{m\,s^{-1}}$
σ_E	25.1	$\mathrm{m\,s^{-1}}$
σ_C	17.6	$\mathrm{m\,s^{-1}}$

Table 2: The Mass and Radius of HD 209458

Model			$\log g$ vs. T_{eff}			M_V vs. $B-V$		
Code	Z	Y	Age (Gyr)	M_* ($M_\odot$)	R_* ($R_\odot$)	Age (Gyr)	M_* ($M_\odot$)	R_* ($R_\odot$)
Geneva	0.02	0.30	4.6	1.15	1.33	6.3	1.08	1.29
Bertelli	0.02	0.27	5.0	1.11	1.31	4.0	1.09	1.30
Claret	0.02	0.28	5.3	1.12	1.31	7.9	1.05	1.27
Yale	0.02	0.27	5.7	1.11	1.31	7.3	1.06	1.28
Yale	0.02	0.30	6.0	1.05	1.27	7.7	1.01	1.25
Geneva	0.008	0.264	9.8	0.94	1.20	12.3	0.91	1.30